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Effects of Continuous-Wave Laser Systems on Stapes Footplate

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Background and Objective: The aim of the present study was to clarify which of the presently available continuous-wave laser systems are best suited for application in stapes surgery.
Study Design/Materials and Methods: Isolated human stapes and bovine compact-bone platelets were used to investigate the connections between the parameters of various laser systems and their effects on bone tissue. The purpose was to optimize the laser parameters required to achieve a perforation measuring 500 μm to 600 μm in diameter. Three different laser systems were applied: the argon and CO_2 laser in continuous wave (cw) mode and the CO_2 laser in superpulse mode.
Results: The suitability of the argon laser for stapedotomy is doubtful in view of the lower absorption coefficient of the stapes for the argon beam and the considerable influence which the degree of pigmentation of the irradiated medium exerts on its effect with the resultant poor reproducibility of the perforation diameter. The beam of the CO_2 laser is far better absorbed at the footplate than that of the argon laser. This results in higher effectivity, lower thermic side effects, and better reproducibility of the perforation. The two modes of the CO_2 laser do not show any appreciable differences.
Conclusion: The experimental results presented indicate that the CO_2 laser in cw and superpulse mode is the most suitable of the systems now clinically applied in stapes surgery.

Key words: argon laser, CO_2 laser, in vitro, laser stapedotomy, laser tissue effect

INTRODUCTION

Complications of the conventional technique of stapedotomy in the therapy of otosclerosis include postoperative hearing loss and, to a lesser extent, irreversible inner-ear damage resulting from manual manipulations with mechanical instruments. This risk is reduced in our study by performing footplate perforation in a non-contact manner with the laser beam. The purpose is to achieve precise and controlled management of middle-ear structures and reduce the incidence of inner ear damage.

The present study aims at examining and describing the tissue ablation capacity of various lasers at the stapes footplate in order to determine the laser type, mode, and the kind of light application that are best suited for stapes surgery and may thus represent a useful alternative to conventional stapedotomy.

In stapes surgery, there have thus far been

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occasional applications of thermically acting lasers (argon, KTP 532, and CO_2 lasers) in continuous wave (cw) and superpulse mode. Their effectiveness and safety still remain a matter of controversy [1–13]. Taking into account previous studies, the results obtained with thermically acting cw lasers are checked and reassessed with appropriate experimental and analytical methods.

MATERIALS AND METHODS

Fifty-two isolated human stapes and 22 bovine compact-bone platelets were investigated to determine the effective laser parameters (wavelength, power, beam diameter, pulse duration, energy) and the suitable application technique (single or multiple application) for achieving a perforation measuring 500 μm to 600 μm in diameter.

The measured transmission spectra of human stapes on the one hand and bovine compact-bone platelets on the other hand show no remarkable differences [5]. For comparable perforation effects with different lasers, the optimal compact-bone footplate thickness was determined to be 90 μm. The use of compact-bone platelets for this study instead of human stapes footplates, which vary widely in their thickness, provided better handling, higher reproducibility of the perforation diameter, and consequently permitted a more exact comparison of laser effects on bone tissue.

Of particular interest, besides the attainable perforation diameters, were the shape and quality of the perforation, the reproducibility of the perforation effect, and the zones of thermic damage at the footplate. In a total of 550 laser applications, the perforation diameters and thermic marginal zones (crystallization, carbonization, and thermic transitional zones) were measured under a stereoscopic microscope (measuring accuracy of 10 μm) and brought in relation to the selected power density. Five measurements were performed at each setting, and the mean value and variation range were determined. Histological processing of decalcified flat sections of the stapes footplate (HE staining) and examinations with the scanning electron microscope (SEM) yielded additional information on the shape and quality (structure) of the perforations and the marginal zones.

Three different laser systems were used: two continuous-wave systems: argon (MDS-83, Aesculap Meditec, Inc., Heroldsborg, Germany) and CO_2 laser (Opmilas 50, Zeiss, Inc., Oberkochen, Germany) and a superpulse system CO_2 laser (1041, Sharplan Lasers, Inc., Tel Aviv, Israel). The laser beam was applied via a micromanipulator.

RESULTS

Argon Laser

The effect of the argon laser, whose wavelength (λ = 488 and 514.6 nm) is poorly absorbed in bone tissue, is highly dependent on the degree of pigmentation of the ablation surface. In the compact-bone model, this leads to a poorly reproducible perforation effect, which is substantiated by the wide variation range of perforation diameters (Fig. 1a). Particularly with shorter pulse durations (0.5 s and 1 s), the perforation diameters vary to such an extent that no reliable statements are possible. An adequately large perforation of 500 μm to 600 μm can only be achieved with a single shot by applying large laser-beam diameters of about 700 μm, power densities of about 1800 W/cm^2 and long pulse times of up to 2 s. The resultant high total energy (14 J to 16 J) causes considerable thermic bone damage.

Figure 2a depicts the obtainable perforation diameters and the resultant thermic damage zones associated with a single laser application at a power density of 900 W/cm^2 and various pulse durations. Striking is the strong prominence of the thermic marginal zones (crystallization and carbonization zone) at a relatively low perforation diameter. A lengthening of the pulse duration from 0.05 to 2 s at a power density of 1800 W/cm^2 effected a slight increase in the perforation diameter with a concomitant doubling of the diameter of the thermic zones as the expression of a considerable thermic exposure of the tissue. A doubling of the power density at the same pulse duration, on the other hand, leads to somewhat larger perforation diameters and smaller thermic marginal zones.

A single application of the argon laser with a large beam diameter (700 μm), a low power density (1800 W/cm^2) and a long pulse duration (0.5–2 s) thus does not seem suitable for a perforation of the footplate.

A reduction of the applied energy by a shortening of the pulse duration to 0.1–0.04 s and a juxtapositioned, slightly overlapping multiple application of high-power-density laser pulses (7500 W/cm^2) in a rosette pattern with a beam diameter of only 160 μm do reduce the thermic exposure but at the same time diminish the re-

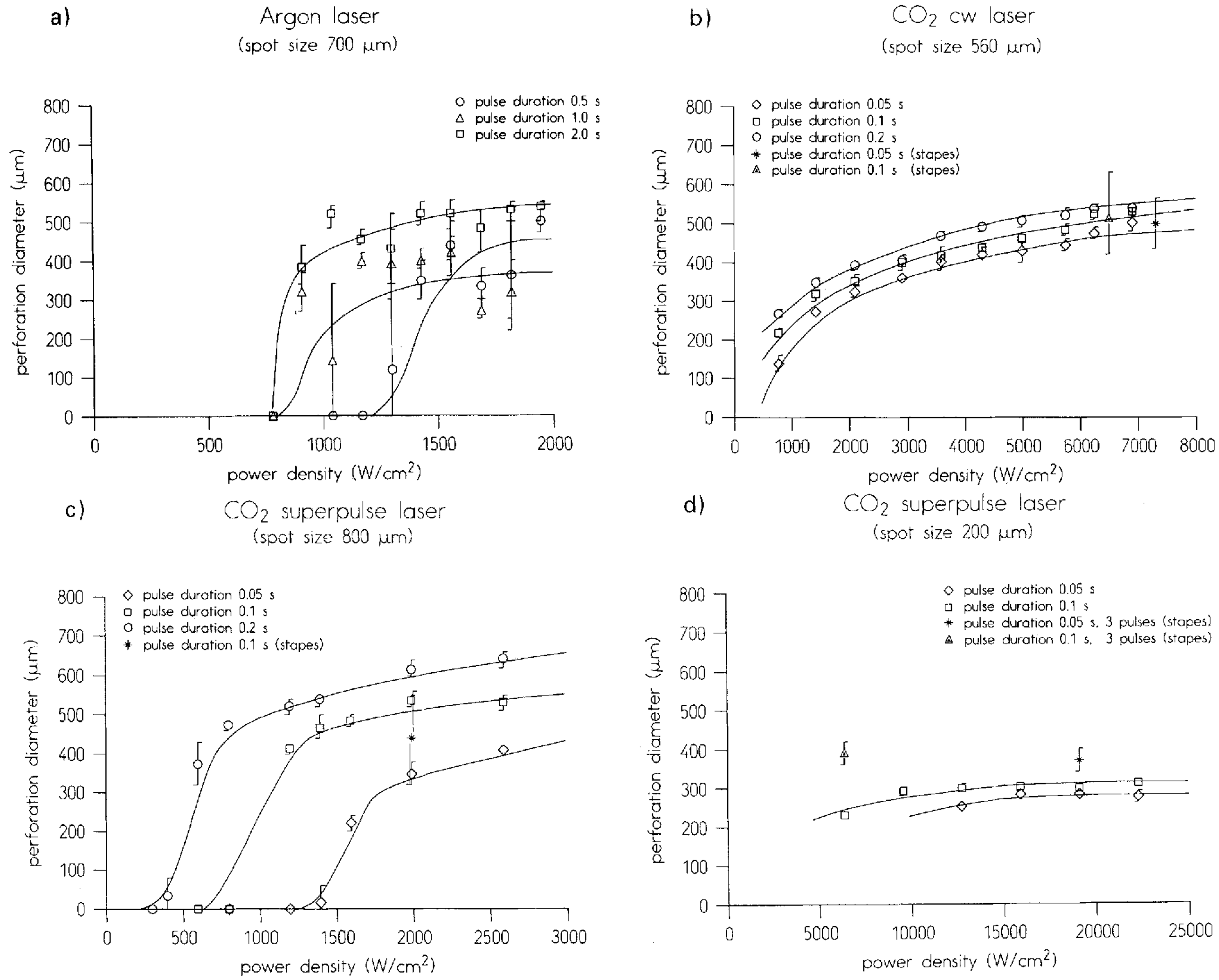

Fig. 1. **Dependence of the perforation diameter on the power density and pulse duration with the (a) argon laser, (b) CO_2 cw laser, (c) CO_2 superpulse laser (beam diameter 800 μm), and (d) CO_2 superpulse laser (beam diameter 200 μm).**

producibility of the ablation process through the formation of crystallization product, which reduces the effectiveness by enhancing reflexion. The high number of single applications (10–20 applications) required for an adequately large perforation measuring 500 μm to 600 μm in diameter causes wide variation of perforation diameters. Multiple crystallization bridges form in the perforation area which cannot be eliminated by renewed laser application but can only be removed instrumentally.

The effective laser parameters determined for multiple application are shown in Table 1.

CO_2 cw Laser

Owing to the high absorption in bone tissue at a wavelength of 10.6 μm, the CO_2 cw laser system achieves good reproducibility of the obtainable perforation diameters. In contrast to the argon laser, it has a function characterized by a relatively low range of variation (Fig. 1b).

The functional connection between the power density and the perforation diameters with various pulse durations is characterized in the CO_2 cw laser by a long flat rising phase, whose slope is nearly independent of the selected pulse durations. Instead, an increase in pulse duration leads to a parallel shifting of function towards larger perforation diameters. Compact bone is already perforated at the lowest power-density setting of about 800 W/cm² (power 1.9 W). The saturation range is not yet reached with a beam diameter of 560 μm and a maximal power density of about 7000 W/cm² (power 18 W). The maximal

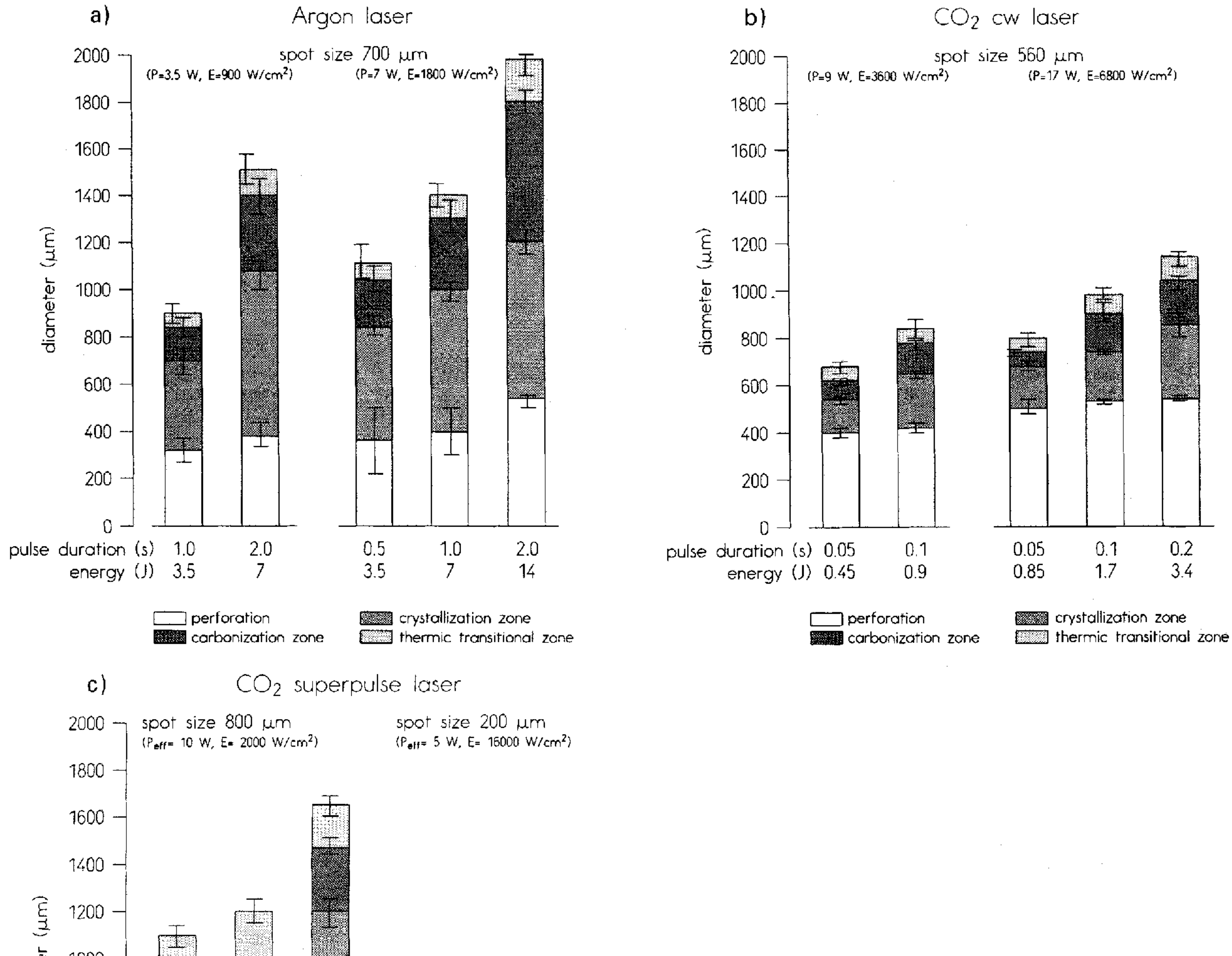

Fig. 2. Dependence of the diameter of the thermically damaged zones on the power density and pulse duration with the (a) argon laser, (b) CO_2 cw laser, and (c) CO_2 superpulse laser.

perforation diameters at this power density are about 500 μm, 530 μm, and 540 μm for pulse durations of 0.05 s, 0.1 s and 0.2 s respectively.

These results clearly demonstrate that a single application of the CO_2 laser requires large beam diameters, high powers, long pulse durations, and thus high energies (approximately 3.5 J) in order to achieve an adequately large perforation measuring 500 μm to 600 μm in diameter.

The perforation diameters at the stapes do not differ appreciably from those in compact bone. The greater variation of stapes-footplate thicknesses caused a somewhat greater variation range of resultant perforation diameters than in the compact-bone model (Fig. 1b).

For a comparable perforation, the degree of carbonization and crystallization relative to the beam diameter is markedly lower with the CO_2 cw than with the argon laser.

The histological picture of the footplate treated with the CO_2 cw laser shows conditions

TABLE 1: Effective Laser Parameters for a Stapes Footplate Perforation Measuring 500–600 μm in Diameter, Taking Into Account the Total Energy Required and the Laser Effect in the Tissue*

Laser system	Beam diameter	Power density	Pulse duration	Number of pulses	Total energy	Perforation quality	Reproducibility	Low thermic side effects
CO_2 (cw) 10.6 μm	≈200 μm	16,000 W/cm^2	0.05 s	4–6	1–1.5 J	+ +	+ +	+ +
CO_2 (superpulse) 10.6 μm	≈200 μm	16,000 W/cm^2	0.05 s	4–6	1–1.5 J	+ +	+ +	+ +
CO_2 (superpulse) 10.6 μm	≈800 μm	2600 W/cm^2	0.1 s	1	1.3 J	+ + +	+ + +	–
CO_2 (cw) 10.6 μm	≈560 μm	6500 W/cm^2	0.1 s	1	1.6 J	+ + +	+ + +	–
CO_2 (cw) 10.6 μm	≈560 μm	3000 W/cm^2	0.05 s	3–5	1.1–1.8 J	+	+	–
Argon 488 + 514.6 nm	≈160 μm	7500 W/cm^2	0.1 s	≈17	≈2.6 J	–	–	–

*+ + + very good; + + good; + satisfactory; – poor.

similar to those seen after applying the argon laser. Here too, tissue alterations and carbonization phenomena are recognizable as the thermic effect of the laser application, but they are less pronounced.

Scanning electron microscopy shows an evenly shaped margin (crystallization zone) with an adjacently wide irregular zone (carbonization zone) (Fig. 3a).

Like the argon laser, the CO_2 cw laser also evidences a distinct dependence of the thermic damage zones on the applied pulse durations. An increase of the pulse duration from 0.05 s to 0.1 s causes a greater enlargement of the thermic damage zones in comparison to the perforation diameter (Fig. 2b).

An increase in the power or power density, on the other hand, appears more effective and involves fewer thermic side effects. Thus, nearly doubling the energy from 0.45 J to 0.85 J by doubling the power leads to a greater increase in the perforation diameter and a relatively less extensive formation of thermic damage zones than doubling the energy by lengthening the pulse duration from 0.05 s to 0.1 s.

With a view to increasing the effectiveness of CO_2 laser footplate management and reducing the thermic side effects, a multiple application was investigated as with the argon laser. A multiply juxtapositioned, slightly overlapping laser application (e.g., 3 applications) makes possible a reduction of the required power density to 3000 W/cm^2, the pulse duration to 0.05 s and thus the single-pulse energy to 0.4 J. This reduces

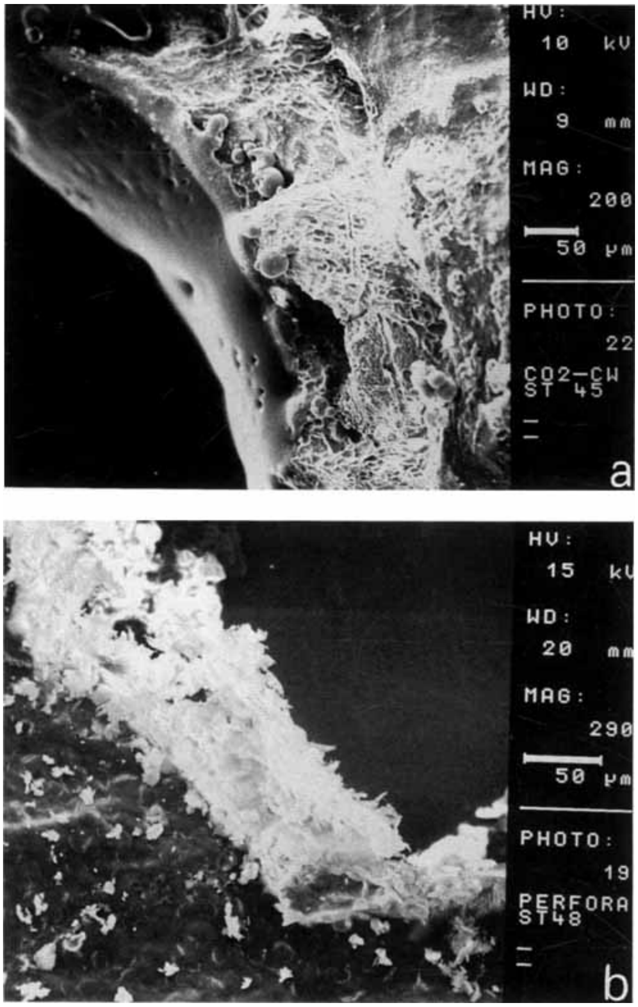

Fig. 3. Scanning electron microscopic image of a footplate perforation with the (**a**) CO_2 cw laser and (**b**) conventional perforator.

Fig. 4. Laser stapedotomy with the CO_2 cw laser (10.6 μm) multiple application; power density: 3 shots at 16,000 W/cm^2; pulse duration: 0.05 s; diameter: perforation = 360–420 μm, irregular crystallization zone, carbonization zone = 560–640 μm, thermic transitional zone = 620–740 μm.

thermic tissue damage but, at the same time, also lowers the reproducibility of the perforation result by decreasing the effectiveness of the laser irradiation through additional reflexion by the formation of crystallization product.

Only a decrease of the beam diameter to about 200 μm leads to a distinct additional reduction of the thermic effects by virtue of a more favorable beam profile and the choice of lower powers with resultant lower energies (Fig. 4). In addition, the practicability of the multiply juxtapositioned perforation technique is increased through a more favorable relation of the laser-beam diameter to the perforation diameter.

For these reasons, when using the CO_2 cw laser, multiple application of juxtapositioned, slightly overlapping single shots with low power, short pulse duration and small beam diameter is better suited for achieving a defined perforation diameter than single application with high power and large beam diameter.

Table 1 shows the effective laser parameters determined for achieving a perforation measuring 500 μm to 600 μm in diameter.

CO_2 Superpulse Laser

The effect of the applied CO_2 superpulse laser system (peak pulse power 300 W, single pulse length 100 μs) is comparable to that of the CO_2 cw system. The mode of application, however, may be expected to reduce thermic tissue damage. A consideration of the perforation effect nevertheless discloses several characteristics that differ in part from those of the CO_2 laser in cw mode (Fig. 1c). The increase of function starting after attainment of the threshold value is markedly steeper with the CO_2 laser in superpulse mode than with the CO_2 laser in cw mode. The phase of steep increase in the obtainable perforation diameters at the onset of function rapidly levels out again on a further increase in power and passes into the saturation range. At the maximally attainable power density of 2600 W/cm^2 and pulse durations of 0.05 s, 0.1 s, and 0.2 s, perforation diameters of 400 μm, 540 μm, and 640 μm respectively will result with a beam diameter of about 800 μm.

The perforation diameters at the stapes footplate are below the 500 μm limit and evidence a wide variation range of about 100 μm.

A reduction of the beam diameter to about 200 μm shifts the attainable power-density range to markedly higher values (Fig. 1d). Starting from a power density of about 16,000 W/cm^2, the maximally achievable perforation diameters are relatively constant and measure about 280 μm–300 μm at pulse durations of 0.05 s and 0.1 s. The variation ranges of the perforation diameters are lower (< 10 μm), which is attributable to a more favorable beam profile of this application system.

Examination of the thermic damage zones shows that application of a large beam diameter of about 800 μm results in high thermic tissue exposure. The thermic effects can also be reduced here by decreasing the beam diameter to about 200 μm (Fig. 2c). This can likewise be ascribed to the more favorable beam profile of the application system and to the lower energies. Moreover, in superpulse mode, the choice of lower mean powers, which reduces the repetition rate from about 450 Hz at 13 W to about 18 Hz at 0.5 W by apparatus-specific alteration of pulse-interval times, leads to an additional reduction of the thermic tissue exposure.

As with the cw mode, multiple application of juxtapositioned, slightly overlapping shots was investigated for its effect. The practicability of performing a triple juxtapositioned laser application to achieve a perforation measuring 500 μm 600 μm in diameter proves extremely problematic when using a large beam diameter (about 800 μm). The formation of crystallization product on applying this beam diameter in compact bone results in very wide variation range of the obtained perforation diameters, so that there is no improvement in the effectiveness and reproducibility of the perforation effect compared to single application.

The CO_2 laser effect with juxtapositioned multiple application can be optimized here too by reducing the beam diameter to about 200 μm. Perforations measuring about 400 μm in diameter can be obtained by triple laser application. Thus, better reproducibility of perforation diameters (variation range 30 μm to 60 μm) can be achieved with this system and technique of application than with the single application technique using a larger beam diameter. A further increase of the pulse count to about 4 to 6 applications results in adequately large perforations of 500 μm to 600 μm.

The results of the perforation experiments have yielded effective parameter constellations that are well suited for achieving an adequately large perforation measuring 500 μm to 600 μm in diameter (Table 1).

DISCUSSION

The aim of our study was to examine the suitability of various continuous wave, thermically acting laser systems for stapes management. Of particular interest was the determination of laser parameters and application techniques that are effective for achieving a footplate perforation measuring 500 μm to 600 μm in diameter. In selecting the parameters, allowances were made for the variation of human footplate thicknesses and the fact that otosclerotically altered stapes footplates are in part more compact and thicker than normal and that their thickness cannot readily be determined in situ. The laser-parameter constellations thus had to be selected in such a way as to ensure effective, reproducible, and hence reliable results even in an "extreme case."

The examined cw and superpulse laser systems (argon and CO_2) offer the advantage that, by an appropriate parameter selection, it is possible to achieve a sufficiently large footplate perforation with one shot or several juxtapositioned, partly overlapping applications. An adverse effect, however, may be seen in the resultant thermic tissue damage. The most favorable power densities proved to be values at the beginning of the saturation range. An increase in power or power density is better suited than a lengthening of pulse duration for achieving a larger perforation diameter and a concomitant relative reduction of thermic side effects. A reduction of the beam diameter will additionally decrease the thermic effects by a lowered requisite power and an improved beam profile. Moreover, more exact positioning of the laser beam is possible with multiple application. We therefore recommend perforating the footplate by juxtapositioning several single shots with low power, a short pulse duration, and a small beam diameter.

The multiple application technique can, however, diminish the reproducibility of the perforation effect of the cw laser systems. This is particularly true for the argon laser, which large amounts of resultant crystallization product can render completely ineffective and thus impracticable for stapedotomy. Moreover, the suitability of the argon laser for stapedotomy is doubtful in view of the lower absorption coefficient of the

stapes for the argon laser beam and the considerable influences exerted on its effect by the degree of pigmentation of the irradiated medium with the resultant overall low reproducibility of the perforation diameters obtained. This also manifests itself in the high total energy of about 2.7 J that is necessary for a sufficiently large perforation diameter of 500 to 600 μm. Nevertheless, the argon and KTP-532 (wavelength 532 nm) lasers are successfully used in clinical practice with the multiple application technique in a rosette pattern [1–4,10–13]. The recommended power densities range from 3000 W/cm^2 to 18,000 W/cm^2 with a pulse duration of 0.1 s. However, the authors do not give exact details about the number of pulses needed and thus the total energy applied for a sufficiently large perforation, which prevents a comparison with our results.

The CO_2 laser beam, on the other hand, is far better absorbed at the footplate than the argon laser beam. This results in higher ablation rates at the bone tissue with correspondingly lower powers. The total energies range between 1 and 1.5 J for both the cw and superpulse mode and are thus markedly lower than with the argon laser wavelength. Compared to the argon laser, multiple application of the CO_2 laser is distinctly better suited for stapedotomy in view of its higher effectivity and lower thermic side effects. With respect to their effects on bone tissue, the two modes of the CO_2 laser system do not show any appreciable differences. A marked additional reduction of the thermic effects at the footplate is not detected in the applied superpulse mode compared to the cw mode.

The effective parameters we worked out for the CO_2 laser are higher by the factor two with respect to the power densities than the "safe laser energy parameters" for stapes footplate perforation specified by Lesinski [7–9]. In agreement with Lesinski, we consider it advantageous to select short pulse duration (0.05 s) and employ the technique of multiple application (3 to 5 applications). He also prefers the superpulse mode with peak pulse powers of 36 W (0.5 J to 0.85 J), 130 W (0.6 J to 1 J), and 280 W (0.3 J to 0.5 J) [7]. More recently, Lesinski has used a superpulse mode with a peak pulse power of 80 W for a single application (0.4 J) [9]. He is of the opinion that, in superpulse mode, the short single pulses (75 μs to 600 μs) and an only short "laser-on time" (5% to 10% of the set pulse duration) as well as the relatively long intervals (2.5 ms – 18 ms) between the pulses results in a decreased tissue heating and thus a lower thermic exposure of adjacent anatomic structures.

A modification of the laser wavelength from 10.6 μm to 9.6 μm increases absorption in the bone tissue (4 to 7 times higher absorption in anorganic components of bone) and, in this way, improves energy coupling to the hard bone substance. Thus it is also able to achieve higher effectivity while reducing thermic damage [14].

Scanning electron microscopy of stapes footplates treated either with the laser or conventionally with a surgical instrument (perforator) demonstrates altogether more favorably shaped perforations with the laser. While the margins of laser perforations tend to be of a smooth and regular structure in the SEM, the picture of a conventionally perforated footplate discloses multiple bone particles projecting into the lumen with a more or less irregular margin configuration (Fig. 3b). Inner ear irritations due to bone particles falling into the vestibule thus appear less probable with laser application.

Reference having been made to the parameters we have determined to be effective, special attention should also be called to the importance of the beam profile and the application system. A flat gaussian profile of the laser irradiation leads to a weaker perforation effect and a stronger formation of thermic marginal zones.

Of the laser systems now applied clinically in stapes surgery, the CO_2 laser in cw and superpulse mode is well suited for stapedotomy according to the results of the present study. The argon laser must be regarded as less suitable because of the less favorable absorption properties of its wavelength in bone tissue.

To be able to make a definitive statement about the most effective laser system for stapes surgery, however, it is necessary to investigate novel types of pulsed laser systems that promise to be suitable for the stapes footplate and act nearly athermically.

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